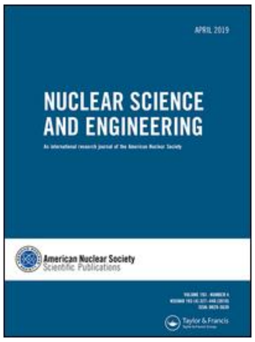

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A High-Assay Low-Enriched Uranium Fuel Transportation Concept

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Abstract — *The uranium ^{235}U enrichment commonly used in fuel production for U.S. light water nuclear reactors typically does not exceed 5 wt%. In contrast, many of the currently investigated advanced reactor concepts demand fuel with higher enrichments. This includes high-assay low-enriched uranium (HALEU), characterized by a ^{235}U enrichment of 5 to 20 wt%. The necessity of HALEU transportation in the fuel production cycle leads to new challenges caused by various technical and regulatory hurdles. Current U.S. Nuclear Regulatory Commission–approved transportation package designs for UF_6 with enrichments above 5 wt% provide relatively small payloads [≤116 kg (250 lb)]. Furthermore, in accordance with 10 CFR 71.55, package design activities for fissile material enriched above 5 wt% need to consider water infiltration in the containment as part of the criticality safety evaluations. This study presents a transportation package concept for HALEU advanced nuclear reactor fuel with a significantly higher payload of up to 376 kg (830 lb) of fissile material per package and up to 1881 kg (4149 lb) of HALEU per legal weight truck. The anticipated chemical form of the transported material is UO_2 downblended from available highly enriched uranium. The concept utilizes a combination of existing transportation packaging, 18 inner canisters, and a novel basket design that includes a borated aluminum flux trap. Criticality and shielding evaluations; fundamental structural, confinement, and thermal assessments; and studies on package operations are presented. The results of this study build significant confidence in the technical feasibility of a high-capacity HALEU transportation package concept while demonstrating the concept's potential to meet U.S. regulatory requirements.*

Keywords — *High-assay low-enriched uranium, advanced nuclear reactor fuel, HALEU transportation, fissile material package, nuclear fuel cycle.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

The typical fuel in current U.S. commercial nuclear power plant light water reactors is UO_2 with an enrichment below 5 wt% ^{235}U. In the fuel production cycle, natural uranium with an enrichment of ≈0.72 wt% (i.e., yellow cake) is converted into UF_6 and sent to an enrichment plant where the ^{235}U concentration is increased, typically to 3 to 5 wt%. After the enrichment, the UF_6 is sent to a nuclear fuel fabrication plant; converted to UO_2; pressed into pellets; and stacked inside the long, hollow cladding of the fuel rods. These rods are bundled together, and the end product is the type of fuel assembly currently used in light water reactors.

In contrast, many advanced reactor concepts currently being investigated for U.S. deployment require fuel with higher enrichments.[1] This leads to new regulatory and technical challenges in designing a transportation package of the fissile material in the fuel production cycle. For instance, the payloads of the standard UF_6 packaging models listed in 49 CFR 173.420 decrease significantly with increased enrichment, providing less than 116 kg (250 lb) of payload to transport UF_6 with enrichment above 5 wt% (Refs. 2 and 3). Other important regulations stated in 10 CFR 71.55 require subcriticality of the package's content even in the most reactive credible conditions during transport, except when

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it comes to transportation packages for UF_6 with an enrichment below 5 wt% {10 CFR 71.55 [g] (Ref. 4)}. As per these provisions, criticality safety evaluations of a high-assay low-enriched uranium (HALEU) package concept need to take into account water leaking into the containment system and potentially complicating the demonstration of subcriticality.[4] Furthermore, the anticipated physical form of the uranium that needs to be transported for HALEU fuel production could be different from that of UF_6.

Currently, only one commercial enrichment facility operates in the United States, namely, Urenco's plant in Eunice, New Mexico.[1] This plant is licensed by the U.S. Nuclear Regulatory Commission (NRC) as a Category III facility, a categorization that speaks to the general quantity limits of special nuclear material that could be stored and handled there.[5,6] Urenco's facility is certified to produce uranium with an enrichment of up to 5.5 wt%, which is significantly below the upper HALEU enrichment limit of 20 wt%. Therefore, other sources of HALEU production are being evaluated to meet near-term advanced reactor fuel demands. An option more readily available is the recovery and downblending of highly enriched uranium (HEU) from used, sodium-bond Experimental Breeder Reactor–II (EBR-II) driver fuel, which could yield HALEU in the form of UO_2 (Ref. 7).

Given the potential need for a high-capacity HALEU transportation concept, the U.S. Department of Energy (DOE) Office of Nuclear Technology Research and Development (NE-4) requested a research collaboration by Idaho National Laboratory (INL), Pacific Northwest National Laboratory, and Oak Ridge National Laboratory (ORNL) to investigate the feasibility of large-scale HALEU transportation. In this paper, the project's activities are presented, including a description of the range of anticipated compositions and uranium vectors for the transported EBR-II HALEU product, along with a summary of the feasibility study on the transportation package concept. The combining of an existing packaging design and a novel basket concept that includes a borated aluminum (DWA's BORTEC®) flux trap and provides space for 18 inner canisters is suggested, providing a payload of up to 376 kg (830 lb) per package. The proposed concept allows transportation of up to five individual packages on the trailer of a single legal weight truck (LWT) in a non-exclusive-use conveyance configuration—with a total payload of up to 1881 kg (4149 lb). The shielding capability and criticality safety of the HALEU package are evaluated; fundamental structural, confinement, and thermal assessments are conducted; and required packaging operations are studied—all to ensure the technical feasibility of the package and demonstrate its potential to meet U.S. regulatory requirements.

II. PACKAGE CONTENT AND DESIGN

II.A. HALEU Composition

Table I describes three HALEU compositions. The data originate from evaluations of six experimental HALEU batches downblended from HEU extracted from used EBR-II fuel. The minimum, maximum, and average fractions of each isotope should envelop the expected HALEU chemical compositions potentially created from this source.[8] The fractions of the uranium isotopes in Table I are given as fractions of the pure uranium quantity in the composition. The fractions of all other elements and isotopes refer to their weight fractions in the final HALEU product. Since this 2018 evaluation, additional work to further remove higher-activity/dose isotopes from the EBR-II HALEU took place (i.e., a procedure called recasting). As such, the compositions in Table I are bounding for shielding and thermal calculations, considering the anticipated material composition available after recasting.[9]

II.B. Concept Design

In 2018, a workshop organized by INL and the Nuclear Energy Institute gathered input from the regulatory and industry stakeholders on important issues related to the establishment of an economical HALEU fuel cycle for advanced reactor concepts in the United States. A concern voiced by participants regarded the timely availability of a HALEU transportation package concept able to provide a large enough payload to be economical.[5] Based on this feedback, the decision was made to initiate research efforts by evaluating currently available transportation packaging designs for fissile material in terms of their potential to be used in a transportation concept to move large (≥1600 kg) amounts of HALEU in a single package or multiple packages on the bed of an LWT. Starting with an existing packaging design should allow for quicker development and licensing of a transportation concept as well as reduce engineering and manufacturing costs. The requirements for the packaging candidates were a small dead load, to facilitate package operations and to optimize the HALEU payload, and the demonstration of a high potential to meet safety requirements imposed by the U.S. regulatory bodies while providing room for input parameter uncertainties intrinsic to the conceptual nature of this project.

TABLE I

Potential HALEU Material Compositions*

Element or Isotope	Average	Minimum	Maximum
Total U (wt%)	99.95	99.89	99.97
Uranium vector ^{232}U (wt ppb U)	0.66	0.07	5.04
Uranium vector ^{233}U (ppb U)	49.12	4.88	318.43
Uranium vector ^{234}U (wt% U)	0.17	0.16	0.21
Uranium vector ^{235}U (wt% U)	19.39	18.97	19.99
Uranium vector ^{236}U (wt% U)	0.58	0.50	1.22
Uranium vector ^{237}U (wt ppb U)	0.06	0.00	0.22
Uranium vector ^{238}U (wt% U)	79.86	79.05	80.36
Zr (wt ppm)	101.45	59.80	146.50
Si (wt ppm)	77.60	40.00	130.00
Y (wt ppm)	6.05	5.00	10.00
Fe (wt ppm)	133.13	39.90	574.00
Cr (wt ppm)	28.15	15.00	115.00
Ni (wt ppm)	43.14	30.00	68.80
Mo (wt ppm)	40.21	10.00	75.00
Mn (wt ppm)	79.47	13.80	190.00
Ru (wt ppm)	77.23	40.00	130.00
Cd (wt ppm)	12.17	5.00	20.00
Al (wt ppm)	101.24	20.00	285.00
Tc (wt ppm)	75.00	65.00	85.00
Li (wt ppm)	15.60	5.00	40.00
K (wt%)	0.05	0.01	0.15
Na (wt ppm)	82.29	35.00	200.00
Ba (wt ppm)	5.00	5.00	5.00
Sr (wt ppm)	5.00	5.00	5.00
^{90}Sr (wt ppb)	15.77	0.31	62.50
Nd (wt ppm)	95.92	25.00	200.00
Sm (wt ppm)	56.82	20.00	160.00
^{99}Tc (wt ppm)	0.15	0.06	0.28
^{135}Cs (wt ppm)	2.67	2.00	3.00
^{54}Mn (wt ppt)	3.04	0.04	12.52
^{60}Co (wt ppt)	27.81	0.27	176.99
^{125}Sb (wt ppt)	102.51	2.88	480.77
^{134}Cs (wt ppt)	24.99	0.23	153.85
^{137}Cs (wt ppb)	8.00	0.55	22.38
^{144}Ce (wt ppt)	67.11	1.88	313.48
^{154}Eu (wt ppb)	0.22	0.00	1.11
^{155}Eu (wt ppb)	0.22	0.00	1.04
^{241}Am (wt ppb)	61.23	2.92	291.55
^{237}Np (wt ppm)	17.11	13.90	21.40
^{239}Pu (wt ppm)	83.57	58.73	103.00
^{240}Pu (wt ppm)	2.24	1.46	2.71

*ppb = parts per billion; ppm = parts per million; ppt = parts per trillion.

II.B.1. Packaging Selection

During the selection process for the packaging design, the activity limits of the expected package content (i.e., the HALEU) had to be considered in determining the required type of packaging to meet U.S. regulations. Two important categories are Type A and Type B packages. Type A packages are designed to survive normal transport conditions and minor accidents. Type B packages, however, are designed to survive severe accident scenarios, which is reflected in their typically more sturdy design.[10] Normal form radioactive material (as defined in 10 CFR 71.4) was assumed; thus, a Type B package is required if the activity of the package content exceeds the activity limit A_2 [Eq. (1)] (Ref. 11):

$$\frac{1}{\sum \frac{f(i)}{A_2(i)}} \leq 1 \quad , \tag{1}$$

where $f(i)$ represents the specific activity of the individual HALEU blend component (i) and $A_2(i)$ represents the corresponding activity limit.[12]

Table II presents a component-wise calculation of A_2 for the average HALEU blend given in Table I. For evaluating the specific activity of a given element in the blend, the natural abundance of that element's isotopes was considered (e.g., 0.012 wt% ^{40}K). Because of the unknown natural abundance of Tc isotopes, the specific activity of pure ^{99}Tc was used to compute the activity of the 7.49E-05 weight fraction of Tc in the blend. The last row of Table II provides the evaluated A_2 quantity for the average HALEU blend, computed according to Eq. (1). The results indicate that Type B packaging is required for transporting more than 3.4 kg of HALEU.

Table III summarizes a decay heat evaluation for the average blend, showing a decay heat Q of less than 1 W per 1000 kg of HALEU. Such a low thermal load should not challenge any packaging design; thus, it was disregarded as a selection criterion.

To achieve optimal flexibility regarding transportation mode, one of the project's self-imposed requirements for developing the HALEU packaging concept is transportability via LWT to achieve optimal flexibility regarding transportation mode.

After extensive review of existing Type B packaging designs using the data in the DOE Radioactive Material Packaging database, three candidates were determined for potential use in a high-payload HALEU transportation concept.[13] The first candidate is the Transnuclear Americas' Long Cask, an NRC-licensed Type B packaging developed for transporting high-burnup used nuclear fuel. The second and third potential candidates are two Type B packaging models from the Optimal Modular Universal Shipping (OPTIMUS$^{\text{TM}}$) series developed by Nuclear Assurance Company (NAC) International: the OPTIMUS for High-Activity Contents (OPTIMUS-H) and the OPTIMUS for Low-Activity Contents (OPTIMUS-L) (Refs. 14, 15, and 16). Eventually, OPTIMUS-L was selected for thorough evaluations because this model provides sufficient shielding while having a lower mass and smaller geometry than the OPTIMUS-H or Long Cask models. These characteristics appeared beneficial to achieve an optimum HALEU payload and facilitate package operations. For instance, multiple individual OPTIMUS-L packages could be mounted on pallets and transported on the bed of a single LWT (i.e., in a non-exclusive-use conveyance configuration), thereby maximizing the amount of transportable HALEU mass. Furthermore, the lightweight OPTIMUS-L could be handled with a normal duty forklift or a crane. Additionally, the OPTIMUS-L design allows loading/unloading while mounted on the truck bed. Note that NAC International's license application for the OPTIMUS-L packaging to the U.S. Department of Transportation is currently pending.[15,17]

Table IV summarizes important OPTIMUS-L characteristics. Graphical representations of the design can be found in various publications online.[14–16]

II.B.2. Canister Concept

The HALEU transportation concept described in this paper combines an existing lightweight packaging design and a novel aluminum basket design. The UO_2 powder is confined within 18 identical stainless steel canisters that are inexpensive to manufacture and can be placed in the basket. Figure 1 presents a sketch of the canister. The canister shell has a cylindrical cross section made from a 3 gauge tube [i.e., with a wall thickness of 5.8 mm (0.229 in.)]. The outer diameter of the tube is 14 cm (5.5 in.). The total canister length is 57.8 cm (22.75 in.). The bottom lid has a thickness of 1.6 cm (0.61 in.) and is welded to the 54.9-cm (21.6-in.)–long canister shell. The four-part top lid assembly includes an annular base that has a thickness of 1.5 cm (0.6 in.), is welded to the canister shell, and has a circular opening with a diameter of 7.6 cm (3 in.). This opening allows for filling the canister with UO_2 powder. The remaining parts of the top lid assembly are a treated closure piece (i.e., a top lid cover) for the opening and two self-energizing, elastomeric O-rings placed between the annular base and the closure piece to seal the canister after loading. Two index marks are incorporated into the closure piece to indicate possible attachment points for remote-handling tools. However, a detailed design of the canister manipulation tools is outside the scope of this current project. The mass of a single empty canister is 14.8 kg (32.6 lb), and the inner volume is approximately 7017 cm^3 (427 in^3.), providing space for 20.9 kg (46.1 lb) of HALEU with a density of 3 g/cm^3 (187.2 lb/ft^3). The mass of a fully filled single canister is 35.7 kg (78.7 lb), and the total mass of the 18 fully filled canisters is 642.7 kg (1417 lb). The total HALEU payload in the 18 canisters is of 376.2 kg (829.4 lb).

II.B.3. Basket Concept

Figure 2 displays the novel basket concept. It consists of two structurally identical sections placed on top of

TABLE II

Evaluation of A_2 Quantity

Element or Isotope	Fraction (wt -)	$f(i)$ (TBq/g)	$f(i)$ (TBq/g_{HALEU})	$A_2(i)$ (TBq)	$f(i)/A_2(i)$ (1/g_{HALEU})
^{232}U	6.59E-10	8.30E-01	5.47E-10	1.00E-03	5.47E-07
^{233}U	4.90E-08	3.60E-04	1.77E-11	6.00E-03	2.94E-09
^{234}U	1.70E-03	2.30E-04	3.90E-07	6.00E-03	6.51E-05
^{235}U	1.94E-01	8.00E-08	1.55E-08	Unlimited	0.00E+00
^{236}U	5.79E-03	2.40E-06	1.39E-08	6.00E-03	2.32E-06
^{237}U	5.99E-14	3.02E+06	1.81E-07	6.00E-02	3.02E-06
^{238}U	7.97E-01	1.20E-08	9.57E-09	Unlimited	0.00E+00
Zr	1.01E-04	0.00E+00	0.00E+00	—	—
Si	7.75E-05	0.00E+00	0.00E+00	—	—
Y	6.04E-06	0.00E+00	0.00E+00	—	—
Fe	1.33E-04	0.00E+00	0.00E+00	—	—
Cr	2.81E-05	0.00E+00	0.00E+00	—	—
Ni	4.31E-05	0.00E+00	0.00E+00	—	—
Mo	4.02E-05	0.00E+00	0.00E+00	—	—
Mn	7.94E-05	0.00E+00	0.00E+00	—	—
Ru	7.71E-05	0.00E+00	0.00E+00	—	—
Cd	1.22E-05	0.00E+00	0.00E+00	—	—
Al	1.01E-04	0.00E+00	0.00E+00	—	—
Tc	7.49E-05	6.30E-04	4.72E-08	9.00E-01	5.24E-08
Li	1.56E-05	0.00E+00	0.00E+00	—	—
K	4.99E-04	1.08E-04	5.39E-08	9.00E-01	5.99E-08
Na	8.22E-05	0.00E+00	0.00E+00	—	—
Ba	4.99E-06	0.00E+00	0.00E+00	—	—
Sr	4.99E-06	0.00E+00	0.00E+00	—	—
^{90}Sr	1.58E-08	5.10E+00	8.03E-08	3.00E-01	2.68E-07
Nd	9.58E-05	0.00E+00	0.00E+00	—	—
Sm	5.68E-05	0.00E+00	0.00E+00	—	—
^{99}Tc	1.50E-07	6.30E-04	9.44E-11	9.00E-01	1.05E-10
^{135}Cs	2.67E-06	4.30E-05	1.15E-10	1.00E+00	1.15E-10
^{54}Mn	3.04E-12	2.90E+02	8.81E-10	1.00E+00	8.81E-10
^{60}Co	2.78E-11	4.20E+01	1.17E-09	4.00E-01	2.92E-09
^{125}Sb	1.02E-10	3.90E+01	3.99E-09	1.00E+00	3.99E-09
^{134}Cs	2.50E-11	4.80E+01	1.20E-09	7.00E-01	1.71E-09
^{137}Cs	7.99E-09	3.20E+00	2.56E-08	6.00E-01	4.26E-08
^{144}Ce	6.70E-11	1.20E+02	8.04E-09	2.00E-01	4.02E-08
^{154}Eu	2.20E-10	9.80E+00	2.15E-09	6.00E-01	3.59E-09
^{155}Eu	2.20E-10	1.80E+01	3.96E-09	3.00E+00	1.32E-09
^{241}Am	6.12E-08	1.30E-01	7.95E-09	1.00E-03	7.95E-06
^{237}Np	1.71E-05	2.60E-05	4.44E-10	2.00E-03	2.22E-07
^{239}Pu	8.35E-05	2.30E-03	1.92E-07	1.00E-03	1.92E-04
^{240}Pu	2.24E-06	8.40E-03	1.88E-08	1.00E-03	1.88E-05
$\sum[f(i)/A_2(i)]$ (1/g_{HALEU}) =					2.90E-04
A_2 (g_{HALEU}) =					3.44E+03

each other to form a basket with a total length of 119.4 cm (47 in.). Each individual section is 59.7 cm (23.5 in.) high and holds up to nine HALEU canisters, for a total capacity of 18 canisters per basket. The main structural components of the basket are made of 6061-T6 aluminum. These components include a circular 1.9-cm (0.75-in.) thick top and a baseplate with a diameter of 82.5 cm (32.49 in.), 1.3-cm (0.5-in.)–thick vertical ribs, and 1.3-cm (0.5-in.)–thick horizontal intermediate ribs that provide lateral stiffness to the vertical ribs.

TABLE III

Evaluation of Decay Heat Q

Element or Isotope	Fraction (wt -)	$f(i)$ (TBq/g)	$f(i)$ (TBq/g$_{\text{HALEU}}$)	$Q(i)$ (W/TBq)	$Q(i)$ (W/g$_{\text{HALEU}}$)
^{232}U	6.59E-10	8.30E-01	5.47E-10	8.68E-01	4.75E-10
^{233}U	4.90E-08	3.60E-04	1.77E-11	7.87E-01	1.39E-11
^{234}U	1.70E-03	2.30E-04	3.90E-07	7.78E-01	3.04E-07
^{235}U	1.94E-01	8.00E-08	1.55E-08	7.50E-01	1.16E-08
^{236}U	5.79E-03	2.40E-06	1.39E-08	7.34E-01	1.02E-08
^{237}U	5.99E-14	3.02E+06	1.81E-07	5.50E-02	9.95E-09
^{238}U	7.97E-01	1.20E-08	9.57E-09	6.86E-01	6.56E-09
Zr	1.01E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Si	7.75E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Y	6.04E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fe	1.33E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cr	2.81E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ni	4.31E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mo	4.02E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mn	7.94E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ru	7.71E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cd	1.22E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Al	1.01E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tc	7.49E-05	6.30E-04	4.72E-08	1.37E-02	6.46E-10
Li	1.56E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
K	4.99E-04	1.08E-04	5.39E-08	0.00E+00	0.00E+00
Na	8.22E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ba	4.99E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sr	4.99E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{90}Sr	1.58E-08	5.10E+00	8.03E-08	2.79E-02	2.24E-09
Nd	9.58E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm	5.68E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{99}Tc	1.50E-07	6.30E-04	9.44E-11	1.37E-02	1.29E-12
^{135}Cs	2.67E-06	4.30E-05	1.15E-10	1.43E-02	1.65E-12
^{54}Mn	3.04E-12	2.90E+02	8.81E-10	1.35E-01	1.19E-10
^{60}Co	2.78E-11	4.20E+01	1.17E-09	4.17E-01	4.87E-10
^{125}Sb	1.02E-10	3.90E+01	3.99E-09	8.61E-02	3.43E-10
^{134}Cs	2.50E-11	4.80E+01	1.20E-09	2.75E-01	3.31E-10
^{137}Cs	7.99E-09	3.20E+00	2.56E-08	3.01E-02	7.71E-10
^{144}Ce	6.70E-11	1.20E+02	8.04E-09	1.77E-02	1.42E-10
^{154}Eu	2.20E-10	9.80E+00	2.15E-09	2.43E-01	5.23E-10
^{155}Eu	2.20E-10	1.80E+01	3.96E-09	1.99E-02	7.88E-11
^{241}Am	6.12E-08	1.30E-01	7.95E-09	9.01E-01	7.16E-09
^{237}Np	1.71E-05	2.60E-05	4.44E-10	7.90E-01	3.51E-10
^{239}Pu	8.35E-05	2.30E-03	1.92E-07	8.41E-01	1.61E-07
^{240}Pu	2.24E-06	8.40E-03	1.88E-08	8.42E-01	1.58E-08
$\sum Q(i)$ (W/g$_{\text{HALEU}}$) =					5.33E-07

Recesses in the plates and ribs reduce the weight of the basket. The top plate has nine circular penetrations equally spaced around the longitudinal basket axis at a radius of 28.3 cm (11.13 in.). These penetrations allow for loading the HALEU canisters into aluminum sleeve tubes that are constructed from 3 gauge tubing with an outer diameter of 15.2 cm (6 in.) and welded to the top and bottom plates of the basket. Each sleeve tube is encased by a hexagonal BORTEC flux trap with a side length of 10.0 cm (3.95 in.) and a wall thickness of 1.3 cm (0.5 in.). These flux trap pipes are not meant to provide any structural support to the basket or canisters.

TABLE IV

NAC International OPTIMUS-L Packaging Characteristics

Dimensions	
Outer packaging diameter	124.5 cm (49 in.)
Outer packaging height	177.8 cm (70 in.)
CCV cavity diameter	82.6 cm (32.5 in.)
CCV cavity height	119.4 cm (47 in.)
Wall thickness stainless steel CCV	2.54 cm (1 in.)
Outer packaging stainless steel inner shell wall thickness	2 mm (0.075 in.)
Outer packaging maximum polyurethane foam wall thickness	17.5 cm (6.875 in.)
Outer packaging stainless steel outer shell wall thickness	5 mm (0.188 in.)
Total (CCV including OP) stainless steel wall thickness	3.2 cm (1.263 in.)
CCV lid bolt diameter	2.54 cm (1 in.)
CCV port cover bolt diameter	6 mm (0.25 in.)
Pallet width	127.0 cm (50 in.)
Outer packaging lid thermal insulation wall thickness	6 mm (0.25 in.)
Materials	
CCV	Stainless steel
Outer packaging shell	Stainless steel
Outer packaging shell/lid/base polyurethane closed cell foam	0.0800 g/cm^3 (5 lb/ft^3)
Outer packaging corner polyurethane closed cell foam	0.3844 g/cm^3 (24 lb/ft^3)
CCV closure bolts	Stainless steel
O-ring material	Elastomer
CCV port cover bolts	Stainless steel
Outer packaging lid outer end plate thermal insulation	Ceramic Fiber
Outer packaging base thermal spider	Copper
Masses and amounts	
Packaging tare weight	2722 kg (6000 lb)
Maximum permitted payload	1429 kg (3150 lb)
Maximum gross weight	4173 kg (9200 lb)
Number of CCV closure bolts	12
Number of O-ring seals	2
Number of lifting lugs at OP lid	3
Number of threaded holes in CCV lid for attaching lifting swivel hoists	3
Other	
CCV lid bolt types	High-strength, socket head cap screws
CCV port cover bolt types	Socket head cap screws
Lifting of loaded package	Use lifting lugs attached to OP lid
Lifting of loaded CCV	Use swivel hoists installed in threaded holes in CCV lid
Tie down of package	Use tie-down arms to secure package on pallet

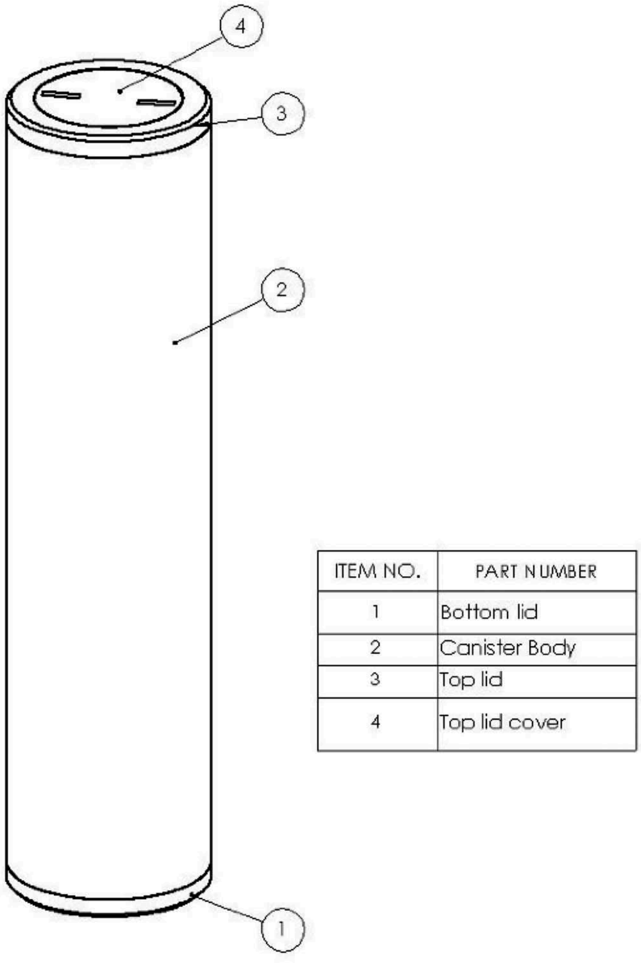
The total mass of the basket assembly (upper and lower sections) is approximately 423.7 kg (934 lb).

After placement, the canisters rest on the basket base plates. The sleeve tubes prevent lateral canister displacements relative to the basket. Vertical displacements of the canisters in the lower basket section are restrained by the upper basket section's bottom plate and for the canisters in the upper basket section, by the inside of the cask containment vessel (CCV) lid.

III. PACKAGE SAFETY EVALUATIONS

III.A. Criticality Safety

Criticality safety evaluations of the proposed HALEU transportation package were conducted utilizing ORNL's Standardized Computer Analyses for Licensing Evaluation (SCALE) software architecture, specifically, the Criticality Safety Analysis Sequence with KENO-VI



ITEM NO.	PART NUMBER
1	Bottom lid
2	Canister Body
3	Top lid
4	Top lid cover

Fig. 1. Canister design.

(CSAS6) code and the Evaluated Nuclear Data File library ENDF/B-VII.1. Furthermore, the applicability of available criticality benchmark data on the proposed concept was studied, utilizing SCALE's Tools for Sensitivity and Uncertainty Analysis Methodology Implementation (TSUNAMI) code.[18] Both evaluation steps were necessary to ensure the criticality safety of the packaging concept, and they are described in detail by Hall et al.[19]

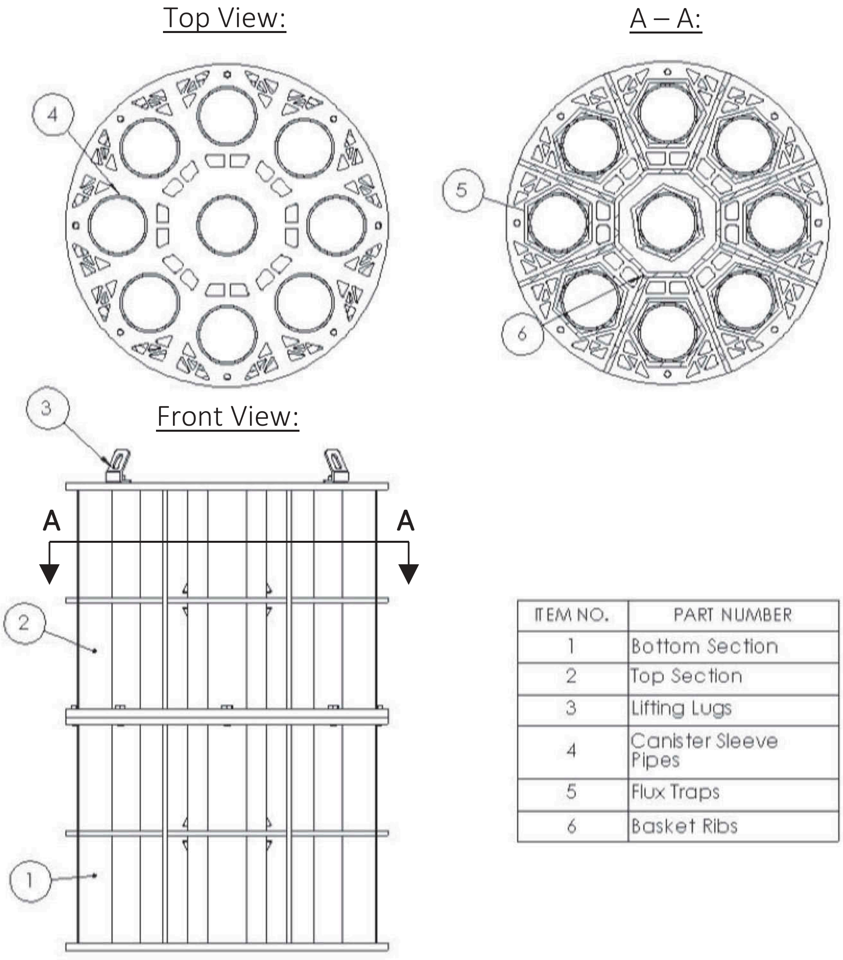
The unit used to measure reactivity is the effective neutron multiplication factor k_{eff}, which is the number of neutrons produced (e.g., due to fission of an isotope) divided by the number of neutrons lost (e.g., due to absorption or leakage) in a system. A k_{eff} of 1.0 implies that the system is critical and in equilibrium between the number of neutrons produced and the number of neutrons lost. In the criticality evaluations, the fissile material was assumed to be pure UO_2 with an isotopic composition of 20 wt% ^{235}U and 80 wt% ^{238}U, disregarding other uranium isotopes or HALEU impurities. This composition is expected to be more reactive than those listed in Table I and provide a bounding value reactivity.

III.A.1. Criticality Evaluations

The goal of the criticality safety evaluations was to identify the most reactive credible package configuration (i.e., the configuration with the highest k_{eff}) in consideration of normal conditions of transport (NCTs) and hypothetical accident conditions (HACs), as defined in 10 CFR 71.71 and 10 CFR 71.73 (Refs. 20 and 21, respectively). Table V summarizes the regulations' applicable package configurations and boundary conditions considered in the evaluations.

The identification of peak k_{eff} included scoping work on a single-package SCALE model (Fig. 3a), potential package array configurations (i.e., to define the array parameter N and to identify the most reactive package spacing), the criticality safety index (CSI) [Eq. (2)], and the temperature. In addition, more detailed investigations were conducted to evaluate the effects of reflective boundary conditions and reduced water densities, between 0 and 1 g/cm^3 [0 and 62.4 lb/ft^3, or 0 to 100% at 293 K (67.7°F)], in various regions of the package. Further, the effect of partial-to-full water flooding of canisters incompletely filled with HALEU was modeled using a variation of the flood water density [from 0 to 1 g/cm^3 (0 to 62.4 lb/ft^3)] along with a variation of the HALEU powder density. Although the assumed UO_2 powder bulk density was 3 g/cm^3 (187.2 lb/ft^3), the package reactivity was evaluated for a bulk density of 0.55 to 10.97 g/cm^3 (34.24 to 648.8 lb/ft^3, or 5 to 100% of the theoretical UO_2 density). These extensive parametric studies were conducted using SCALE's SAMPLER sequence, an application that can be used to investigate the effects of input parameter variations or uncertainties in CSAS6 (Ref. 18)

Results of the criticality evaluations suggest that of the NCT and HAC configurations analyzed, an HAC packaging configuration had the highest system reactivity. The most reactive configuration is a 2 × 7 hexagonal array (i.e., $N = 7$) of damaged packages in close contact, with no water in the spaces between the packages, and outer packaging (OP) foam thickness reduced from 17.46 cm (6.875 in.) to 1 cm (0.394 in.) to simulate OP damage due to the accident (Fig. 3b). Boundary conditions around the array during this HAC are modeled as a 30-cm (11.811-in.)–thick ring of water (with a density of 1000 kg/m^3 [62.4 lb/ft^3, or 100% at 293 K (67.7°F)]). Maximum reactivity occurs if the packaging cavity is dry, but the HALEU canisters are filled with a uniform mixture consisting of 15 wt% UO_2 [10.97 g/cm^3 (648.8 lb/ft^3)] and 85 wt% water [1 g/cm^3 (62.4 lb/ft^3)]. The computed k_{eff} value for this configuration is 0.912, which should be sufficiently subcritical to allow



ITEM NO.	PART NUMBER
1	Bottom Section
2	Top Section
3	Lifting Lugs
4	Canister Sleeve Pipes
5	Flux Traps
6	Basket Ribs

Fig. 2. Basket design.

for increases related to code bias, bias uncertainty, manufacturing tolerances, and minor temperature effects (all outside the scope of this work) and meet the $k_{eff} < 0.95$ subcriticality requirement as per NUREG-1609 (Ref. 22).

The CSI can be computed with Eq. (2):

$$\mathrm{CSI} = \left\lceil \frac{50}{N} \right\rceil \ , \tag{2}$$

which yields a value of 8 for a single package.[23] This limits the maximum number of packages transportable per single LWT to six in order to meet the $\sum \mathrm{CSI} \le 50$ threshold of 10 CFR 71.59. Note that the maximum k_{eff} under NCTs is less than 0.81. The results of the evaluations suggest that criticality safety of the proposed transportation concept consisting of five fully loaded packages on a single LWT can be achieved under the limiting assumption of a 20 wt% ^{235}U, 80 wt% ^{238}U mix.

III.A.2. Criticality Benchmark Applicability

During the design process, questions arose as to the applicability of currently available criticality benchmark data on safety evaluations of HALEU transportation packages. To address this concern, the correlation between a set of 1584 available criticality benchmark experiments and the most reactive NCT and HAC packaging configurations was evaluated.[19] The TSUNAMI evaluations recognized 34 experiments as being similar to the identified NCT configuration and an additional 666 as being marginally similar. Furthermore, the evaluations recognized 55 experiments as being similar to the most reactive HAC configuration and an additional 1104 as being marginally similar. The results of Hall et al. indicate that enough criticality benchmark data are available for criticality safety evaluations of the presented HALEU package design.[19]

TABLE V

Regulatory Requirements for Criticality Safety of a Transportation Package

Regulation	Corresponding Package Configurations and Boundary Conditions
10 CFR 71.55	Most reactive credible package configuration Most reactive credible water moderation Close full reflection by water or surrounding packaging material
10 CFR 71.59	5 × N undamaged packages with nothing in-between or 2 × N damaged packages remain subcritical considering optimum interspersed hydrogenous moderation. Further: Close full reflection of the 5 × N or 2 × N array by water $N \geq 0.5$ $\sum \mathrm{CSI} \leq 50$
10 CFR 71.71	NCT: Ambient temperatures between −233.15 K (−40°F) and 311.15 K (100°F)
10 CFR 71.73	HAC: Free drop, crush, and thermal tests affect criticality through loss of package spacing due to damage to—or loss of—overpack materials.

III.B. Shielding Evaluations

Radiation shielding evaluations were conducted to ensure radiological protection of both operating personnel and the public during transportation. A pretransportation HALEU storage period of 1 day was assumed, and SCALE's Oak Ridge Isotope Generation (ORIGEN) code was used to determine the neutron and gamma source inventory that remained from the maximum HALEU compositions listed in Table I (Ref. 18). To achieve conservative dose rate results, a HALEU density in the canisters of 6.7 g/cm^3 (418.3 lb/ft^3) was assumed, which is significantly higher than the expected density of 3.0 g/cm^3 (187.2 lb/ft^3), for a total of 803.8 kg (1772 lb) of HALEU in each individual package. The reason for choosing such a high density can be found in Sec. III.C.

After source term determination with ORIGEN, SCALE's Monaco with Automated Variance Reduction using Importance Calculations (MAVRIC) code was used for the shielding evaluations, along with ENDF/B-VII.1 nuclear cross-section data and ANSI/ANS-6.1.1-1977 (N666) ("Neutron and Gamma-Ray Flux-to-Dose Rate Factors," American Nuclear Society, La Grange, Park, Illinois) gamma and neutron flux-to-dose conversion factors.[18]

The proposed package arrangement with five packages placed in a single row on the LWT trailer is displayed in Fig. 4. The goal was to meet the 10 CFR 71.47 NCT and 49 CFR 177.842 dose rate limits for a non-exclusive-use conveyance configuration that allows transportation of multiple individual packages on a single LWT (Refs. 24 and 25, respectively). The HAC dose rate limits of 10 CFR 71.51 were also evaluated.[26] Table VI summarizes the considered regulations, including corresponding dose rate limits. Three different analysis models were used to evaluate the regulatory compliance:

1. The first model includes a single undamaged package to check 10 CFR 71.47 compliance.
2. The second model includes a single damaged package to check 10 CFR 71.51 compliance. The damage was modeled by disregarding the overpack in the evaluations.
3. The third model includes an array of 5 × 1 undamaged packages to simulate the desired LWT transportation configuration and check 49 CFR 177.842 compliance.

All three models assume a dry air volume around the package(s) and take into consideration the maximum HALEU composition according to Table I. Table VII summarizes the results of the shielding evaluations. The peak dose rate for a single undamaged package model is less than 0.3 mSv/h (30 mrem/h), which is below the 2 mSv/h (200 mrem/h) limit in 10 CFR 71.47. The peak dose rate for a single undamaged package 1 m away from the surface [i.e., the transport index (TI) (see Table VI)] is 0.06 mSv/h (6 mrem/h), which is below the 0.1 mSv/h (10 mrem/h) limit in 10 CFR 71.47. The peak dose rate for the single damaged package is approximately 1.01 mSv/h (101 mrem/h) at the external package surface, and it is 0.121 mSv/h

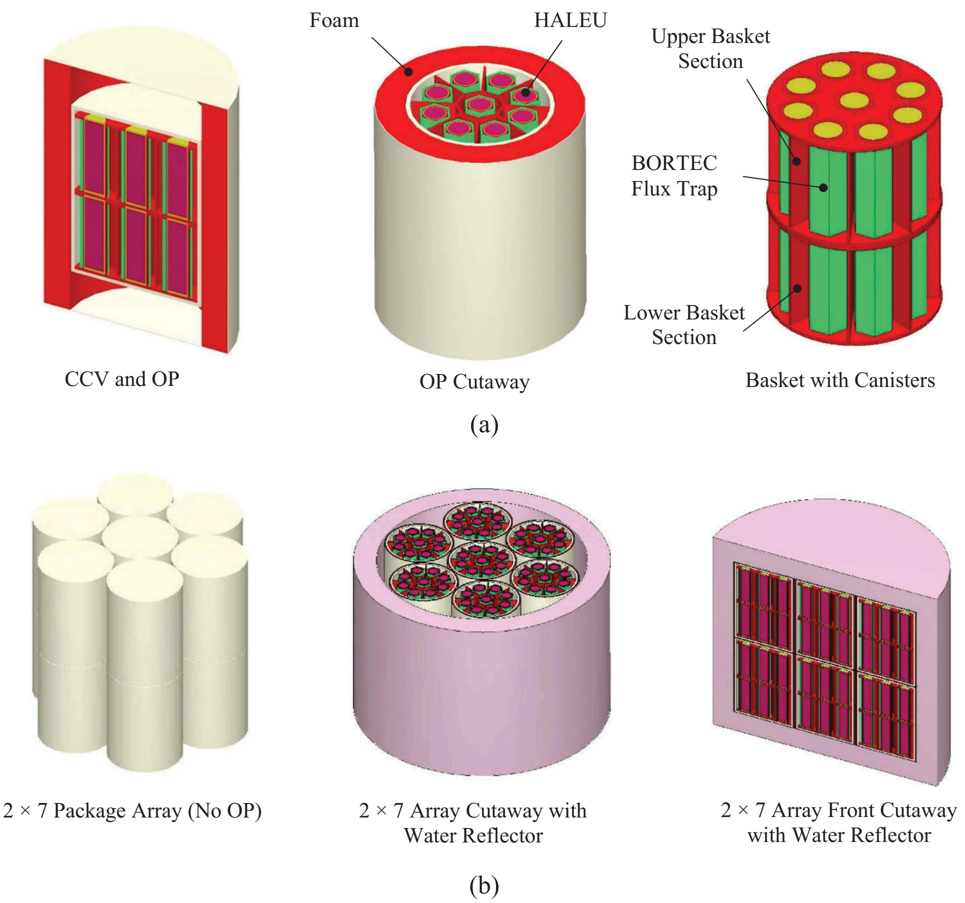

Foam
HALEU
Upper Basket Section
BORTEC Flux Trap
Lower Basket Section
CCV and OP
OP Cutaway
Basket with Canisters
(a)
2 × 7 Package Array (No OP)
2 × 7 Array Cutaway with Water Reflector
2 × 7 Array Front Cutaway with Water Reflector
(b)

Fig. 3. Views of (a) single package and (b) 2 × 7 package array HAC criticality model.

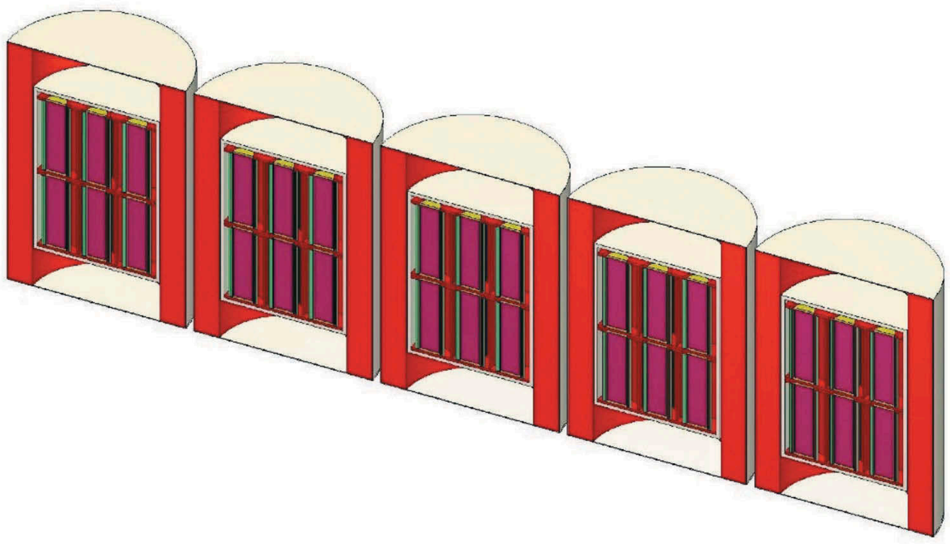


Fig. 4. Cutaway view of model used to evaluate dose rate for 5 × 1 LWT transportation array.

(12.1 mrem/h) 1 m away from the surface, which is below 10 CFR 71.51's limit of 10 mSv/h (1 rem/h) 1 m away from the surface.

Figure 5 displays the gamma dose rate spatial distributions for the 5 × 1 LWT transportation array model in two dimensions (Fig. 5a horizontal and Fig. 5b

TABLE VI

Regulatory Dose Rate Limits for Radiation Shielding for a Non-Exclusive-Use Conveyance Configuration

Regulation	Corresponding Dose Rate Limits
10 CFR 71.47	Dose rate ≤2 mSv/h (200 mrem/h) at any point on the external surface of the package TI ≤ 10, which is a limit equivalent to 0.1 mSv/h (10 mrem/h) at 1 m from the external surface of the package
10 CFR 71.51	HAC dose rate ≤ 10 mSv/h (1 rem/h) at 1 m from the external surface of the package
49 CFR 177.842	∑TI ≤ 50

TABLE VII

Dose Rate Evaluations*

Undamaged Single Package			
Location	Gamma	Neutron[a]	Total
Surface	0.2940	0.0030	0.2970
1 m from surface	0.0590	0.0005	0.0595
Damaged Single Package			
Location	Gamma	Neutron[a]	Total
Surface	1.0000	0.0080	1.0080
1 m from surface	0.1200	0.0009	0.1209
Transportation Array			
Location	Gamma	Neutron[a]	Total
Surface	0.6000	0.0030	0.6030
1 m from surface	0.1700	0.0006	0.1706

*In units of mSv/h.

[a] Includes subcritical neutron multiplier = 10.

vertical), using a 10 × 10-cm mesh size. The data suggest that the dose rate is higher between the packages as well as at the center of the package's top and bottom. The peak dose rate is approximately 0.6 mSv/h (60 mrem/h) at the surface of the 5 × 1 LWT transportation array, and it is 0.17 mSv/h (17.1 mrem/h) 1 m away from the surface (i.e., ∑TI = 17.1). Thus, 49 CFR 177.842 regulations are met. The results of the presented shielding evaluations indicate that radiological safety for the proposed transportation concept can be achieved.

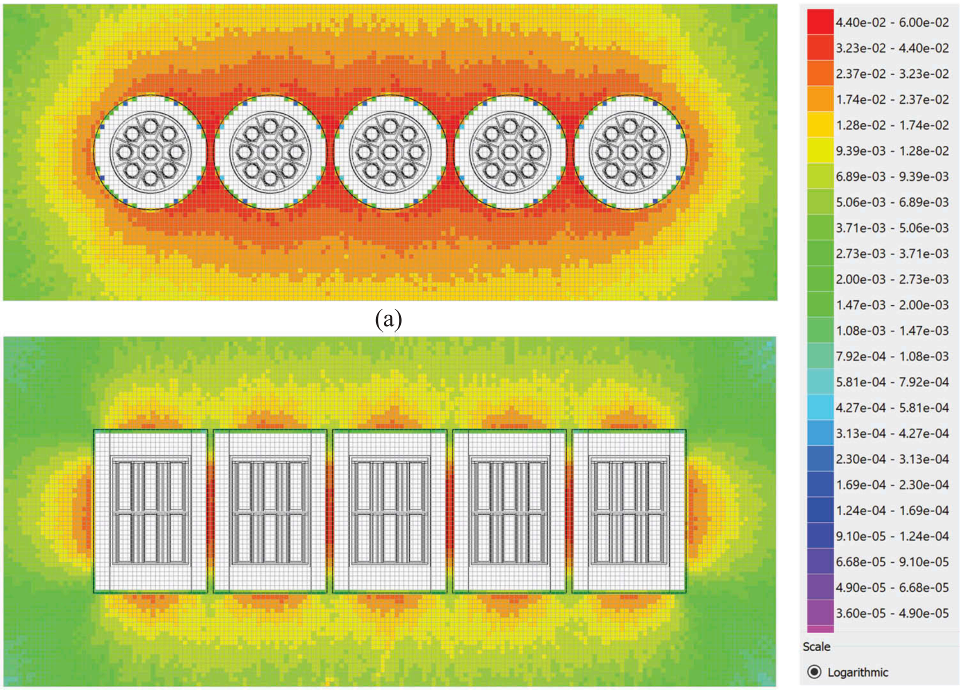
III.C. Structural Evaluations

Fundamental structural evaluations of the transportation package concept were performed using finite element (FE) models. Because of the conceptual nature of the design developed in this research initiative, detailed analyses of the package response under 10 CFR 71.71 (NCTs) and 10 CFR 71.73 (HACs) were out of scope, and the following assumptions were made to gain confidence in the structural integrity of the package under manageable evaluation effort:

1. A UO_2 powder density of 6.7 g/cm^3 (418.3 lb/ft^3) should lead to a conservatively high mass of the CCV internals without exceeding the OPTIMUS-L payload capacity.

2. Energy dissipation due to deformations of the OPTIMUS-L CCV was disregarded. The CCV was represented by a rigid body in the FE models, causing absorption of the entire impact energy by the basket and canister structure, which should lead to a robust basket design.

3. For licensing purposes, the OPTIMUS-L packaging underwent extensive structural evaluations. Thus, it can be assumed that this packaging can uphold its structural integrity under 10 CFT 71.71 (NCT) and 10 CFR



(a)

(b)

Fig. 5. Spatial gamma dose rate distribution for the 5 × 1 LWT transportation array shielding model—(a) horizontal and (b) vertical—using a 10 × 10-cm mesh size (rem/h).

71.73 (HACs) since the accumulated mass of the CCV internals does not exceed the package payload limit.

These assumptions allowed for putting the investigative focus on the effects that package drops have on the CCV internals. Furthermore, it is important to note that the presented structural evaluations considered a 7.6-cm (3-in.)–shorter basket than the design in Fig. 2. The canisters of the evaluated structure are 3.8 cm (1.5 in.) shorter than the canister design in Fig. 1. These geometric deviations are consequences of the development process of the package concept: During initial scoping work, no reliable information on the expected UO_2 density could be identified, and the assumption of a high UO_2 density of 6.7 g/cm^3 (418.3 lb/ft^3) (≈60% of the theoretical density) and fully loaded HALEU canisters was deemed appropriate to achieve a conservative structural assessment. However, this conservatism also caused the need for a lighter basket and canisters to prevent the sum of their masses from exceeding the payload capacity of the OPTIUMS-L packaging. Consequently, the decision was made to design and evaluate a slightly shorter basket and canisters than the CCV height of 119.4 cm (47 in.) would allow. Nevertheless, additional investigative efforts indicated a bulk powder density of not more than 3 g/cm^3 (187.2 lb/ft^3) for UO_2 oxidized from uranium, in addition to the feasibility of a 119.4-cm (47-in.)–long basket.[27] While recognizing the slight geometrical deviations from the design proposed in Secs. II.B.2 and II.B.3, the presented methodology should have yielded conservatively large deformations and plastic stresses in the evaluated structure, due to the assumption of a very high HALEU density.

Table VIII summarizes the regulatory NCT and HAC drop scenarios considered in the structural evaluations. Although this list of scenarios is not comprehensive, the assessed HAC package drops are expected to lead to peak accelerations of the CCV internals and, therefore, provide valuable insight into their structural responses to extreme loading scenarios.

III.C.1. Evaluation Criterion

Because of the conceptual nature of the proposed design, no rigid design criterion was defined for the presented structural evaluations. However, to boost confidence in the feasibility of a potential HALEU transportation concept aligned to the proposed design, the following parameters were studied in the FE simulations:

1. the effective plastic strains in the canisters and basket structure
2. the relative canister spacing with respect to the as-designed configuration.

TABLE VIII

Evaluated Package Drop Scenarios

Regulation	Evaluated Package Drop Scenario
10 CFR 71.71	NCT: Free drop distance of 1.2 m (4 ft) Flat, essentially unyielding, horizontal impact surface End and side impact of package
10 CFR 71.73	HAC: Free drop distance of 9 m (30 ft) Flat, essentially unyielding, horizontal impact surface End, side, and center of CGOC impact of package

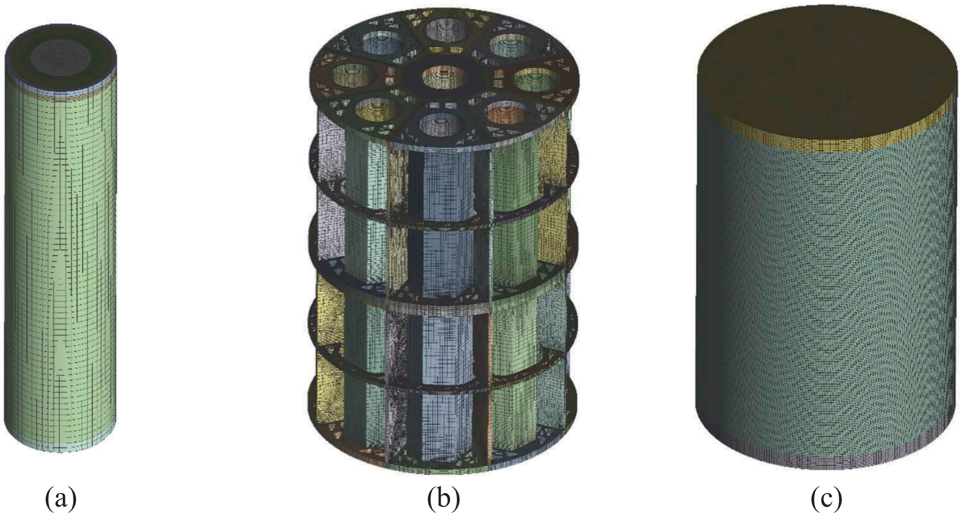
The effective plastic strains were chosen due to the increased use of strain-based acceptance criteria in current package design processes as per the *ASME Boiler Pressure Vessel Code* (BPVC) (e.g., WB-3700 in BPVC. III.3-2019) (Ref. 28). Excessively large strains in the basket or canister components could cause the need for significant structural modifications to the proposed package concept during continued design efforts. Furthermore, a remarkable decrease in relative HALEU canister spacing due to a package impact could cause the need for design modifications to ensure criticality safety of the package or potentially lead to dismissal of the transportation concept proposed in this study.

III.C.2. Finite Element Modeling Approach

An FE model geometry was developed using Dassault Systèmes' computer-aided design software SOLIDWORKS™ 2018. This geometry was subsequently exported to Ansys, Inc.'s Workbench for meshing. Then, Livermore Software Technology Corporation's explicit FE solver, LS-DYNA® R8.1, was used to compute the strains in the canister and basket.

The developed geometry included detailed models of the canisters (one of the 18 is displayed in Fig. 6a) and the basket (Fig. 6b). However, the OPTIMUS-L packaging was not modeled, and a rigid, cylindrical CCV body (Fig. 6c) was instead used to represent the interaction between the packaging and the CCV internals. This approach was expected to yield conservatively high strains in the basket and canisters since it required the kinetic energy built up during a package drop to dissipate entirely via the basket and canister deformations.

Figure 6 also displays the meshes developed using eight-node hexahedral elements and six-node wedge elements. In total, 1 862 701 elements were generated



(a) (b) (c)

Fig. 6. Geometry and mesh of the considered FE model components: (a) exemplary canister, (b) basket, and (c) CCV.

using these meshes. Welds between the components were represented in the model by fully bonded elements. It is important to note that the BORTEC flux trap pipes were not bonded to the base and top plates of the basket since they were not intended to support the basket structurally. Contact between the canisters and the basket and between the basket and the CCV was modeled using LS-DYNA's automatic two-way surface-to-surface functionality.

III.C.3. Material Properties

Table IX provides a summary of the material properties (Young's modulus E, yield strength f_y, Poisson's ratio ν, and density ρ) used in the FE model representations of the Type 304L stainless steel (SS304L) canisters and the 6061-T6 aluminum components of the basket. The mass of the UO_2 powder in the fully loaded canister was incorporated into the density of the SS304L canister tube. The material properties were derived from data provided in ASME BPVC.II.D.C-2019 and ASME BPVC Code Case N-519 (Refs. 29 and 30, respectively). In the event that the stress in the steel or aluminum exceeds the corresponding yield strength during the analyses, nonlinear material behavior is expected. The curves in Fig. 7 describe the relationships between the plastic strains and the stresses in both materials after the yielding points used in the FE model.

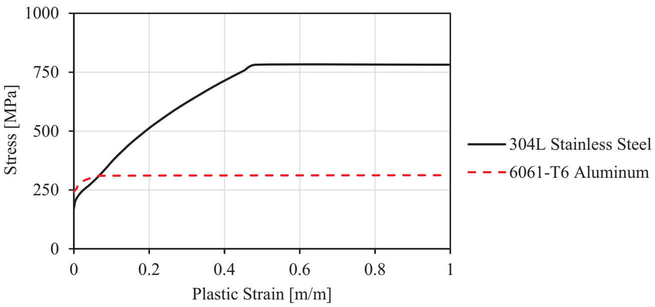


Fig. 7. Plastic strain versus stress in SS304L and 6061-T6 aluminum.

The hexagonal, neutron-absorbing flux trap pipes were not designed to carry any load apart from supporting their own weight under accelerations caused by the analyzed package impacts. Thus, in the FE simulations, linear BORTEC behavior was assumed. The BORTEC flux trap material is essentially a boron carbide (B_4C)–reinforced aluminum metal-matrix composite. Other than the yield strength [f_y = 137.9 MPa (20 ksi)] for different B_4C volume fractions, no material property data for BORTEC are available.[31] Therefore, the inverse rule of mixtures was used to predict a lower bound for its Young's modulus along with upper bounds for its density and Poisson's ratio as follows:

$$\frac{1}{x_c} = \frac{V_m}{x_m} + \frac{V_f}{x_f} \tag{3}$$

and

$$x_c = V_m x_m + V_f x_f \quad , \tag{4}$$

where

x_c = BORTEC property
V_m = volume fraction of the aluminum matrix
x_m = aluminum matrix property
V_f = volume fraction of the B_4C (assumed to be 30%)
x_f = B_4C property.

Table X provides a summary of the derived material properties.

III.C.4. Acceleration Time Histories

The time histories of Fig. 8a represent the accelerations applied on the rigid CCV body of the FE model to simulate the effects of the considered NCT

TABLE IX

Material Properties to Represent the Stainless Steel and Aluminum Components

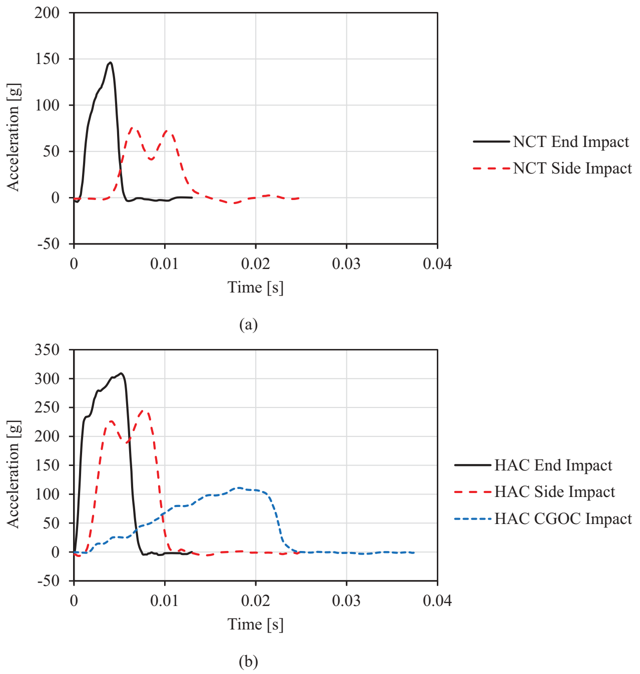
Material	E	f_y	ν	ρ
SS304L canister bottom and top lids	195 000 MPa (28 282 ksi)	172 MPa (24.9 ksi)	0.31	8.03 g/cm^3 (501.3 lb/ft^3)
SS304L canister tube, including HALEU mass	195 000 MPa (28 282 ksi)	172 MPa (24.9 ksi)	0.31	34.09 g/cm^3 (2128.2 lb/ft^3)
6061-T6 aluminum basket components	67 200 MPa (8992 ksi)	240 MPa (34.8 ksi)	0.33	2.7 g/cm^3 (168.6 lb/ft^3)

TABLE X

Material Properties Used to Represent the BORTEC Flux Traps

Material	E	f_y	ν	ρ
6061-T6 aluminum	67 200 MPa (8992 ksi)	240.0 MPa (34.8 ksi)	0.33	2.7 g/cm^3 (168.6 lb/ft^3)
B_4C	362 000 MPa (52 503 ksi)	—	0.18	2.52 g/cm^3 (157.3 lb/ft^3)
BORTECH with 30% B_4C	88 930 MPa (12 898 ksi)	137.9 MPa (20.0 ksi)	0.31	2.646 g/cm^3 (165.2 lb/ft^3)

drops assuming a free drop height of 1.2 m (4 ft) and a package end or side impact. The time histories of Fig. 8b represent the accelerations applied on the CCV to simulate the considered 9-m (30-ft) HAC package drops in light of package end, side, and gravity-over-corner (CGOC) impacts. The data of Figs. 8 and 9 were provided by NAC International and derived in the structural evaluations of the OPTIMUS-L package by recording CCV acceleration during these simulations.[32] Table XI summarizes the peak accelerations reached during these simulations, suggesting that the highest accelerations of the package are expected for a 9-m (30-ft) free drop with an impact on the package end.



(a)

(b)

Fig. 8. Accleration time histories used for evaluation of (a) NCT drop resulting in package end and side impacts and (b) HAC drop resulting in package end, side, and CGOC impacts.

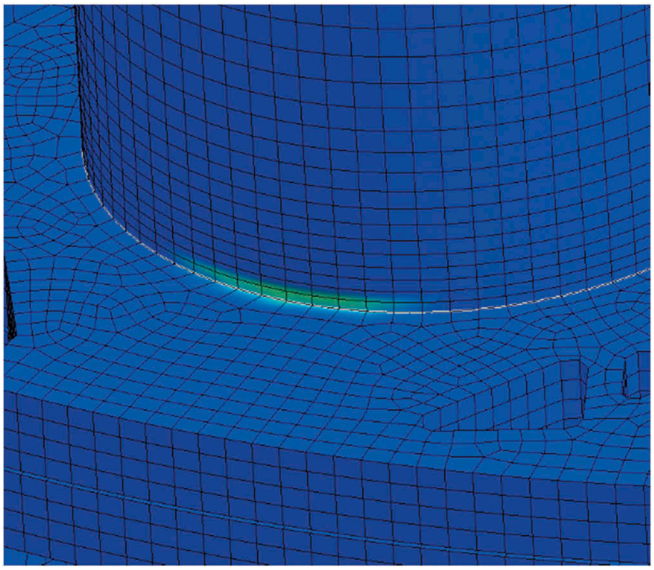


Fig. 9. NCT side drop: zones of sleeve pipe affected by plastic strains.

III.C.5. Plastic Strains

Table XII summarizes the maximum effective plastic strains reached in the different structural components of the canisters and basket in the considered NCT and HAC package drop scenarios. The highest strain considering NCT is reached in the canister sleeve pipes when a package side impact is assumed. The affected zone is located close to the connection between the sleeve pipe and the base plate (Fig. 9). Other components that experience plastic deformations in NCT loading are the basket base plates, canister tubes, and canister lids. However, in none of these components did the computed effective plastic strains exceed 1.51%. Thus, it was concluded that a fully

TABLE XI

Peak CCV Accelerations During Considered NCT and HAC Package Drop Scenarios

Scenario	Peak Acceleration (g)
NCT: package end impact	146
NCT: package side impact	76
HAC: package end impact	309
HAC: package side impact	247
HAC: package CGOC impact	111

elastic structural response of the canisters and baskets under NCT loading could be achieved in the final design.

Considering HACs, a maximum effective strain of 3.86% is reached in the aluminum base plates of the basket. For comparison, typically achieved values for the ultimate elongations of SS304L are approximately 70% and range between 12% and 17% for 6061-T6 aluminum.[33,34]

During HACs, a minor fraction of less than 0.14% of the BORTEC flux trap pipe volume experienced stresses exceeding the material's yield strength. Considering the inherent conservative assumptions made during the modeling process, the BORTEC pipes can be expected to remain intact during package impact. The results of the evaluations indicate that a sound structural design for the proposed concept is achievable with minimum effort.

III.C.6. Relative Canister Spacing

Computations found that the relative changes in canister center-to-center spacing under impact loading were within 0% to 0.5% and, therefore, insignificant. The minimum canister spacing remained between 21.3 cm (8.375 in.) and 21.4 cm (8.43 in.). Thus, no criticality safety concerns were identified in these evaluations.

III.D. Containment and Confinement

The CCV of the OPTIMUS-L is a 2.5-cm (1-in.) stainless steel vessel with a bolted top lid, sealed with two elastomeric O-rings. The CCV represents the regulatory containment barrier for the packaging content, and it can be expected to have undergone rigorous evaluations in the scope of the license application process.

Confinement of the UO_2 in the 18 canisters is important for safe canister operational procedures. It is provided by the canister welds, and the two self-energizing O-ring seals between the top lid annular base and the top lid cover along with significant plastic deformations in the cover would indicate the potential for a loss of confinement. The FE simulations computed the peak effective plastic strains in the cover to be less than 2E-05 (Table XII). It is important to note that no plastic strains were detected in the simulations of the NCT package drop scenarios, indicating low risk of unexpected release of fissile material into the CCV and suggesting sufficient confinement capabilities built into the package concept.

III.E. Thermal Evaluations

The decay heat computation presented in Table III indicates a low decay heat of 5.33E-07 W/g of HALEU blend. For a given maximum HALEU payload of 376 kg (830 lb) per package, the total heat generation in the package is a negligible 0.02 W, indicating that the package's safety functions are not challenged by the content's heat load.

It can be expected that during the license application process, the OPTIMUS-L package underwent extensive thermal assessments including investigations on the effects of extremely high temperatures caused by a 10 CFR 71.73 HAC fire event. This assumption allows for identification of potential safety concerns due to effects of extreme temperatures on the basket and canister structures by comparing an estimated maximum CCV temperature with the permitted continuous-use temperature for SS304L, 6061-T6 aluminum, and BORTEC, as per ASME BPVC.II.D.C-2019, ASME BPVC Code Case N-519, and Wang (Ref. 35) (Table XIII).

The maximum CCV temperature was taken as the maximum permissible service temperature of the elastomeric O-rings of the CCV because they are likely part of the most challenged OPTIMUS-L components in a fire event simulation. This service limit temperature, however, depends on the type of O-ring elastomer (Table XIV). The most heat-resistant rings identified are made of Viton and can withstand temperatures of up to 477 K (399°F). Thus, the maximum CCV temperature is likely limited to 477 K (399°F). This limit does not exceed the maximum continuous-use temperatures of SS304L and 6061-T6 aluminum [700 K and 477 K, or 800°F and 399°F, respectively (see Table XIII)]. The BORTEC flux trap material can withstand temperatures of up to 573 K (572°F).

Although the thermal evaluations presented above are of a very elementary nature, results suggest that more sophisticated thermal evaluations of the proposed

TABLE XII

Peak Effective Plastic Strains Computed for the Considered NCT and HAC Package Drop Scenarios

Maximum Effective Plastic Strain (m/m)					
	NCT		HAC		
Component	End Impact	Side Impact	End Impact	Side Impact	CGOC Impact
Sleeve pipe	0.00E+00	1.51E-02	1.66E-04	2.40E-02	3.40E-03
Support structure	2.50E-04	0.00E+00	2.00E-03	1.60E-03	0.00E+00
Base plates	0.00E+00	1.24E-02	4.01E-04	3.86E-02	2.64E-04
Canister sides	2.50E-03	1.10E-03	7.40E-03	3.00E-03	1.81E-04
Canister top lid	5.00E-06	1.00E-03	2.12E-04	3.70E-03	4.40E-04
Canister top lid cover	0.00E+00	0.00E+00	1.89E-05	0.00E+00	0.00E+00
Canister bottom lid	3.00E-03	4.20E-03	7.40E-03	1.22E-02	4.00E-03

TABLE XIII

Permissible Continuous-Use Temperatures for Basket Component Materials

Material	Type	Maximum Continuous-Use Temperature
SS304L	Seamless tube	700 K (800°F)
SS304L	Forgings	700 K (800°F)
6061-T6 aluminum	Seamless tube	477 K (399°F)
6061-T6 aluminum	Plate/sheet	477 K (399°F)
BORTEC	Plate/sheet	573 K (572°F)

TABLE XIV

Maximum Service Temperature Limits of Commonly Used O-Ring Materials

O-Ring Material	Maximum Service Temperature
Ethylene propylene copolymer	423 K (302°F)
Viton	477 K (399°F)
Fluorosilicone	473 K (392°F)

package concept in the final design process could demonstrate its capability to withstand the regulatory range of extreme temperatures.

III.F. Package Operations

Procedures for loading and unloading the canisters need to be developed, but such processes should be conductible using remote actuators or hand tools. The threaded lid cover allows reusability of the HALEU canisters.

Depending on the operational requirements of the utilized HALEU and fuel fabrication facilities, the basket sections could be individually loaded with the filled canisters and subsequently stacked within the OPTIMUS-L packaging; otherwise, the basket bottom section could be placed in the packaging before being loaded with the canisters followed by the same routine for the top section. Another option would be to place empty canisters in the basket sections before being filled with HALEU. After stacking the basket sections on top of each other, the basket sections are connected with interface bolts to prevent relative translations and rotations of individual sections with respect to each other. Although the removeable lifting lugs and basket section interface bolts are indicated in the sketches of Fig. 2, detailed designs or analyses of these parts, the tools required, and the basket lifting and loading operations are outside the scope of the current project.

The OPTIMUS-L package includes tie-down points that meet 10 CFR 71 requirements and can be used to mount the cylindrical package vertically on the transportation pallet. Multiple pallets can be mounted on a single LWT trailer. Because of the small, lightweight nature of the individual packages, no heavy or specialized lifting equipment is necessary during the loading process.

IV. HALEU PAYLOAD OF TRANSPORTATION CONCEPT

In developing the transportation package, the goal was to achieve a high HALEU payload but provide room to accommodate input parameter uncertainties without causing immediate safety concerns or rejection of the concept design. The maximum permitted payload in a single OPTIMUS-L packaging is 1429 kg (3150 lb) (see Table IV). The sum of the mass of the basket structure [423.7 kg (934 lb)] (see Sec. II.B.3) and the total mass of the 18 fully filled canisters [642.7 kg (1417 lb)] [assuming a HALEU density of 3 g/cm^3 (187.2 lb/ft^3)] (see Sec. II.B.2) is 1066.4 kg (2351 lb), which is significantly below this limit.

The sum of the mass of a single empty OPTIMUS-L package [2721.6 kg (6000 lb)] (see Table IV) and the total mass of the basket and the 18 fully loaded canisters is 3788 kg (8351 lb). This is well below the permitted maximum gross weight of 4173 kg (9200 lb) (see Table IV) for OPTIMUS-L.

As shown in Sec. III.B, the computed radiation levels of the proposed array of five packages meet the 10 CFR 71.47 thresholds for a non-exclusive-use conveyance configuration, allowing transportation of at least five packages on a single LWT. Current U.S. regulations limit the gross vehicle weight of an LWT to 36 287 kg (80 000 lb). Trucks with a gross weight below this threshold do not require a special overweight permit.[36] The payload of a five-axle, semi-trailer, 36 287-kg (80 000-lb) LWT can be roughly estimated as 22 679.6 kg (50 000 lb), which should be enough capacity to transport five fully loaded OPTIMUS-L packages with a total weight of 18 940 kg (41 755.5 lb) plus accompanying pallets and tie-down equipment.

Thus, the presented transportation concept provides a HALEU payload of 376.2 kg (829.4 lb) per individual package and 1881 kg (4146.9 lb) per LWT when using an array of five individual packages and assuming a UO_2 bulk powder density of 3 g/cm^3 (187.2 lb/ft^3).

V. SUMMARY

A novel design for a HALEU transportation concept was presented, and an evaluation of the primary safety functions and operations was conducted. The assumed HALEU material is downblended UO_2 harvested from EBR-II used nuclear fuel. The concept utilizes a combination of existing packaging (NAC International OPTIMUS-L) and a novel basket design that provides room for 18 individual HALEU canisters. The basket is made of 6061-T6 aluminum and utilizes BORTEC flux traps around the canister sleeve pipes for criticality control. Up to five individual canisters can be transported on an LWT in a nonexclusive conveyance configuration without requiring a special overweight permit.

The presented criticality safety evaluations identified the most reactive configuration as an HAC that includes a 2 × 7 hexagonal array of damaged packages in close contact with no water in the spaces between the packages and an OP foam thickness reduced to 1 cm (0.394 in.). Boundary conditions around the array during this HAC are modeled as a 30-cm (11.811-in.)–thick ring of water. Maximum reactivity occurs if the packaging cavity is dry, but the HALEU canisters are filled with a uniform mixture of 15 wt% UO_2 and 85 wt% water. The computed k_{eff} value for this configuration is 0.912, which is below the 0.95 limit for criticality safety as per NUREG-1609. The CSI limits the maximum number of packages transportable on a single LWT to six.

The peak dose rate for a single undamaged package 1 m away from the surface is 0.06 mSv/h (6 mrem/h). The peak dose rate for the single damaged package is approximately 1.01 mSv/h (101 mrem/h) at the external package surface and 0.121 mSv/h (12.1 mrem/h) 1 m away from the surface. The peak dose rate is approximately 0.6 mSv/h (60 mrem/h) at the surface of the 5 × 1 LWT transportation array and 0.17 mSv/h (17.1 mrem/h) 1 m away from the surface. Thus, 10 CFR 71.47, 10 CFR 71.51, and 49 CFR 177.842 regulations are met. Shielding evaluations also indicate the possibility of a non-exclusive-use conveyance configuration for the concept.

Explicit FE simulations indicate the development of effective plastic strains of less than 2% in the structural components of the basket and canisters during simulated NCT package drops and less than 4% during simulated HAC package drops. The identified plastic zones are very localized. In anticipation of using a strain-based acceptance criterion in a potential final design for the transportation concept, the magnitude of these plastic strains appears acceptable for a conceptual design. The relative changes in canister center-to-center spacing during the simulated package drop scenarios were insignificant. Negligible plastic deformations of the canister lid indicate that the canisters can maintain confinement during package operations, NCT, and HAC.

The package content's low heat load of less than 0.02 W does not challenge the OPTIMUS-L packaging design. Thermal evaluations indicate that the basket, canisters, and flux trap materials can withstand the regulatory extreme temperature ranges necessary to achieve Type B licensing.

Multiple potential package operational procedures were discussed, demonstrating the flexibility of the proposed concept. The expected maximum HALEU payload is 376.2 kg (829.4 lb) per individual OPTIMUS-L package and up to 1881 kg (4146.9 lb) when loading five individual packages onto a single LWT.

VI. CONCLUSIONS

Based on the investigations described in this study, it can be concluded that the proposed HALEU transportation concept remains subcritical under all evaluated HAC and NCT conditions, provides sufficient radiological protection to the operating personnel and the surrounding environment, is structurally sound, contains and confines the HALEU, sustains the expected thermal loads, and can be successfully operated—all of which are indications for a high potential for successful licensing. However, the presented evaluations are of a preliminary nature, and future research and development efforts are required to create the final, deployable design.

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